NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-762

The Use of Conventional Wind Tunnels to Simulate Planetary Atmospheric Aerodynamics

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The aerodynamic effects of planetary atmospheric simulation have been experimentally investigated in the Jet Propulsion Laboratory wind tunnels. Admixtures of carbon dioxide into the conventional dried air working fluid were used to simulate variations of the atmospheric properties. The performance of the wind tunnels, the techniques used, and samples of the data obtained are presented. The results obtained indicate that, within a given range, this approach will yield excellent data for planetary atmosphere entry vehicle design.

Author

I. INTRODUCTION

A major task assigned to the Jet Propulsion Laboratory is the unmanned exploration of planets. While fly-bys and orbiters provide some information, it seems apparent that planetary surface landers will be required. In order to survive landing, the planetary atmospheres must be traversed, and the exploration vehicle must be decelerated to arrive at the surface at a moderate velocity. The aerodynamic behavior of the exploration vehicle in these atmospheres will be a significant factor in its successful landing.

In preparation for the design phase of planetary exploration vehicles, the JPL wind tunnels have been used to investigate working fluid composition effects on vehicle aerodynamic performance. These two continuous-flow closed circuit wind tunnels normally operate with dried air as the working fluid; the 20-in. supersonic wind tunnel (SWT) covers a Mach number range of from 1.3 to 5.6, and the 21-in. hypersonic wind tunnel (HWT) covers a Mach number range of from 4.1 to 11.0 at stagnation temperatures up to 1350°F. Reference 1 describes these facilities in more detail.

Carbon dioxide was chosen as a contaminant in the normal dried air working fluid of these wind tunnels for several reasons:

1. Its relatively low cost and easy availability.
2. Its inoffensive properties with regard to toxicity, flammability, corrosiveness, and chemical stability.
3. Its significantly different physical properties from air, such as molecular weight, isentropic exponent, etc.

While the atmospheres of Mars and Venus are expected to contain carbon dioxide, their exact compositions are still somewhat uncertain. The effects on aerodynamic performance of the working fluid properties obtainable by air-carbon dioxide mixtures are expected to be illustrative of nearly any atmosphere encountered.

II. SPECIAL EQUIPMENT AND INSTRUMENTATION

In order to provide air-carbon dioxide mixtures in the wind tunnels, the handling and controlled introduction of carbon dioxide into the tunnel circuit and the accurate measurement of the carbon dioxide concentration in the testing area were the main operational problems. Reference 2 describes several initial attempts to solve these problems. Only the most satisfactory methods will be described here.

Figure 1 illustrates the method for the introduction of carbon dioxide into the tunnel circuit. Liquid carbon dioxide in large insulated pressurized containers was

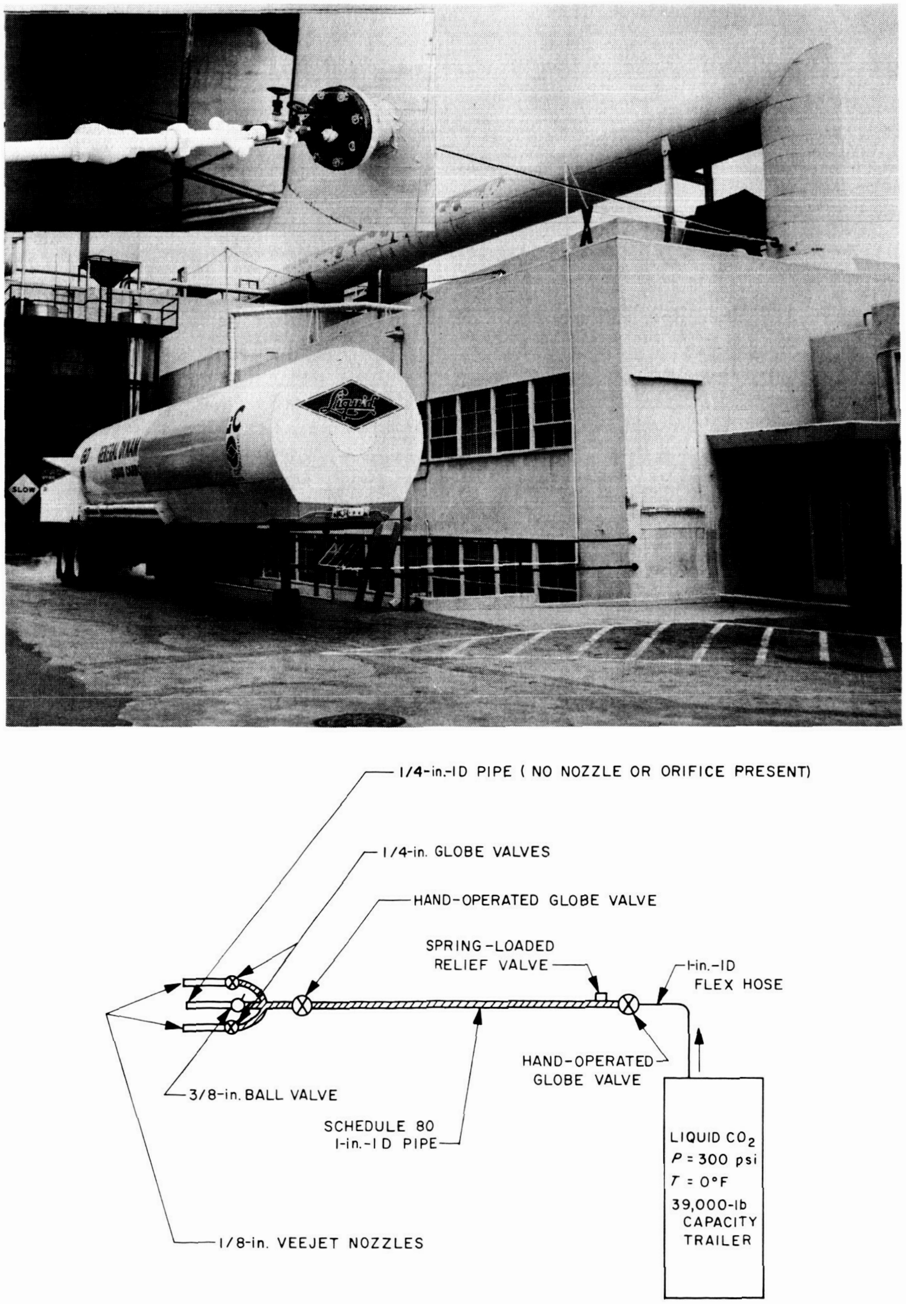

Fig. 1. Successful CO_2 supply system for the Supersonic Wind Tunnel

obtained. This liquid carbon dioxide was continuously injected into the tunnel circuit in the low pressure return leg. Injecting the carbon dioxide at this point had two advantages: the relatively low pressure enhanced evaporation of the liquid, and the compressor plant with its multiple stages of rotary compressors and intercoolers, large circuit volume, and length, provided extensive mixing. Figure 2 shows the carbon dioxide entering the tunnel working fluid as a spray from several Veejet nozzles. The flow rate, up to 3 lb/sec, was manually controlled by three parallel valves of graduated sizes, the largest having a ⅜-in.-diameter straightthrough port. Back pressure from the Veejet nozzles prevented solid carbon dioxide from forming in these control valves. Experience showed that carbon dioxide levels of up to 80% by volume could be obtained, although some practice was necessary to learn how to hold a preselected level. (A block diagram of the system used in determining volume percent of carbon dioxide is shown in Fig. 3.) Compressor motor loading increased about 10% at high carbon dioxide levels. Up to 20 minutes were required to build up to the high carbon dioxide levels.

The air-carbon dioxide mixture levels were continuously monitored by an infrared analyzer (Ref. 3) connected to a bleed from the wind tunnel settling chamber. This instrument had previously been calibrated using samples of known composition (see Fig. 4 for a readout calibration plot). In addition, spot checks of the mixture ratio were made with conventional Orsat absorption equipment and occasional samples were sent to the chemistry laboratory for spectroscopic analysis. The repeatability and agreement between these various types of measurement indicate that, when properly used, any one of them will yield adequate results.

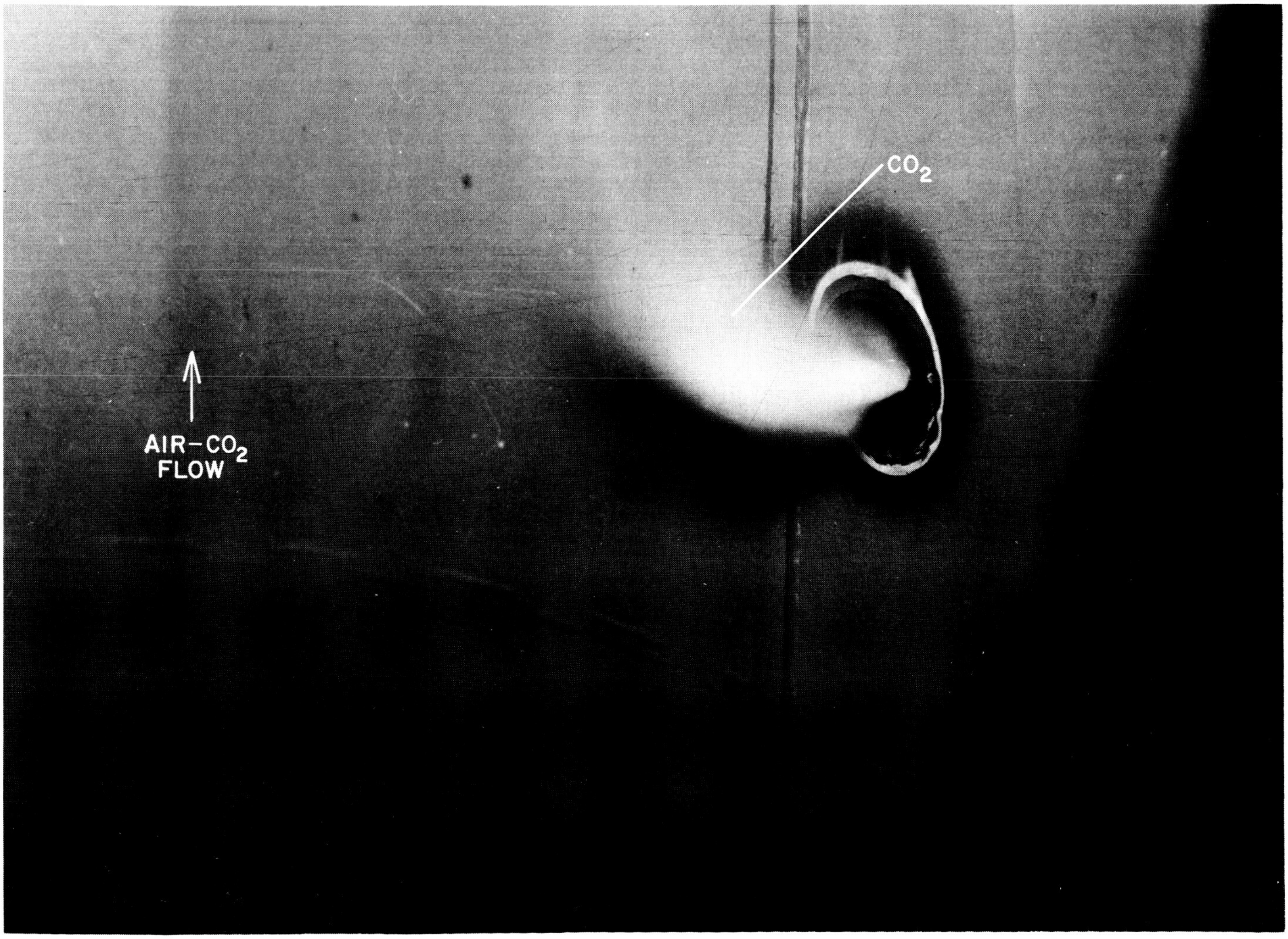

Fig. 2. CO_2 entering the return pipe downstream from the SWT diffuser

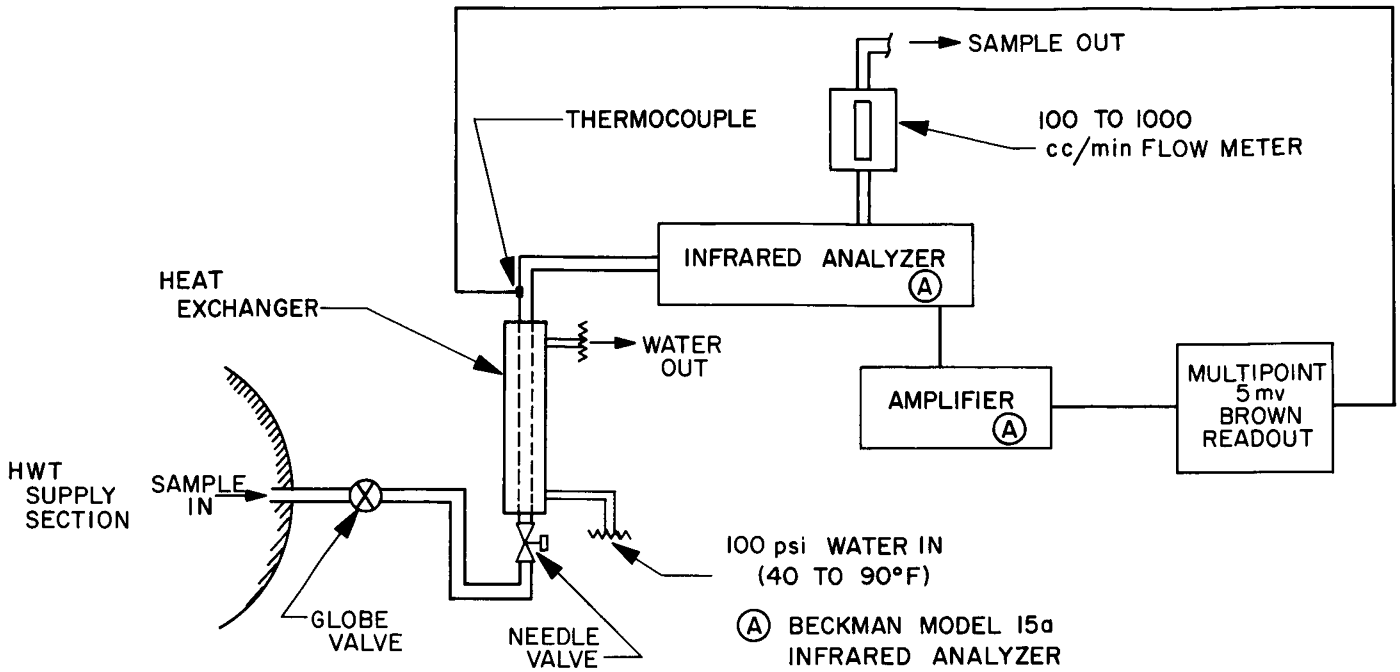

Fig. 3. System for determining percent CO_2 by volume

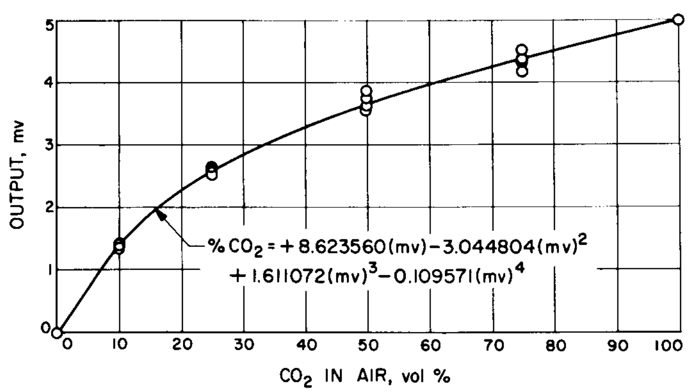

Fig. 4. CO_2 readout calibration curve of system of Fig. 3, using known composition samples

III. AERODYNAMIC RESULTS

Condensation in the working fluid constitutes one upper limit on the Mach number range of wind tunnels. This limit is the major reason for removing water vapor from the air in a wind tunnel. Carbon dioxide, having a condensation temperature between water and dried air, provides an upper Mach number restriction between water and dried air. Reference 4 discusses this problem, and presents an analytical method for predicting this limitation. Figure 5 presents the applicable results of this analysis. Assuming:

1. Appreciable amounts of carbon dioxide are present.
2. Negligible carbon dioxide supersaturation.
3. Maximum stagnation temperature of 1350°F available in the hypersonic wind tunnel (HWT) due to heater limitations.

This figure indicates that the HWT may be limited to a maximum Mach number of about 6.5, rather than 11.0 as with dried air.

Figure 6 presents experimental confirmation of this analytical limitation. At Mach number 5, supply pressure 515 cm of Hg absolute, with 11.6% of carbon dioxide present (60 cm of Hg absolute carbon dioxide partial pressure), Fig. 5 predicts a minimum temperature of

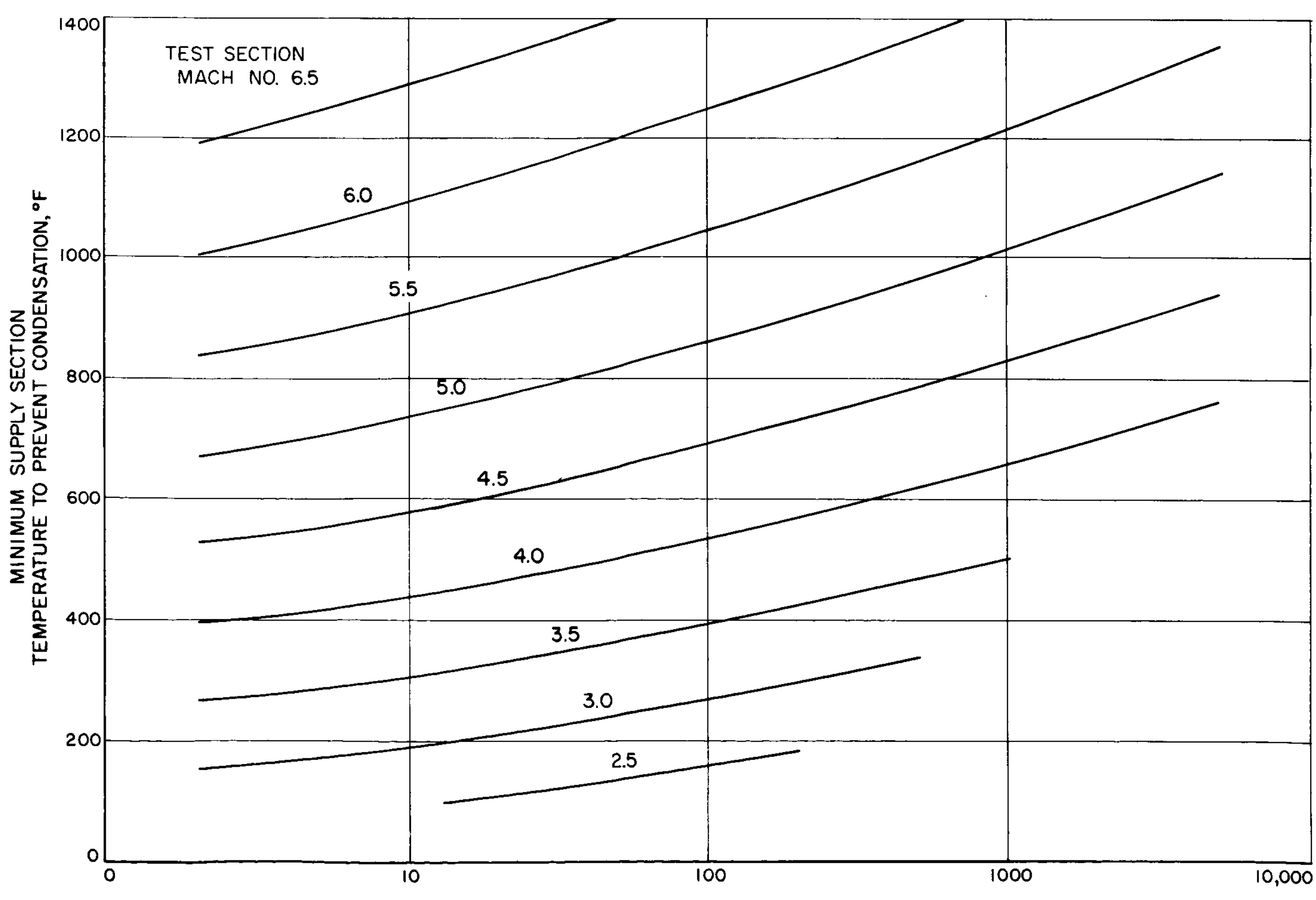

Fig. 5. Predicted CO_2 condensation according to Ref. 4

(Equilibrium conditions, no supersaturation, $\gamma = 1.34$ constant)

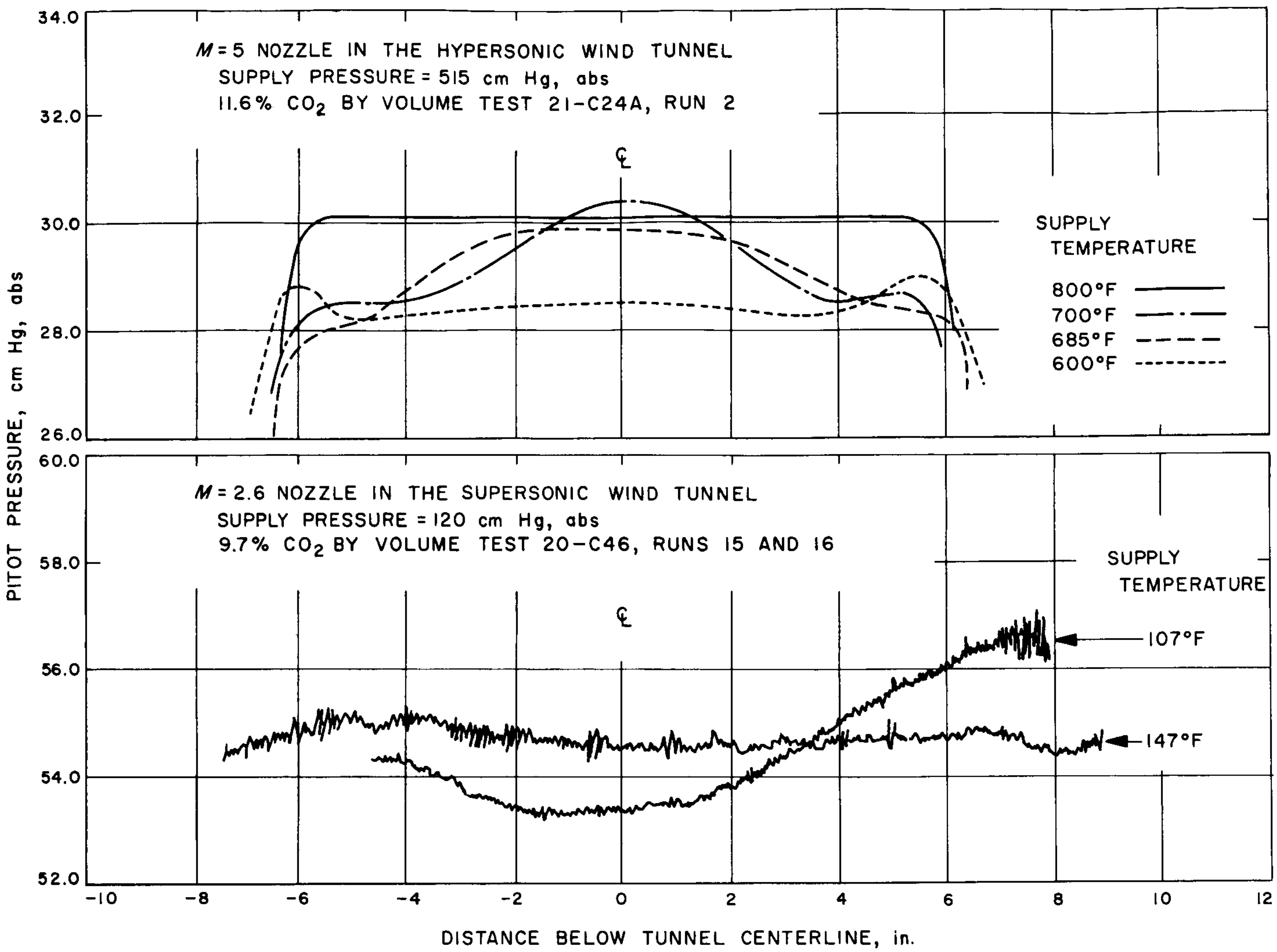

Fig. 6. Liquefaction effects of CO_2-air mixture on pitot-pressure distribution

835°F required. Figure 6 shows that 800°F was sufficient to yield satisfactory pitot pressure traces, but 700°F and below yielded unsatisfactory results typical of the presence of air or water condensation. The discrepancy between the 800°F and 835°F indicates either a small amount of supersaturation or a (not unexpected) partial breakdown of Raoult's law of mixtures. As in the HWT, the example presented for the SWT confirms the analysis; at Mach number 2.6 and a carbon dioxide partial pressure of 11.6 cm of Hg absolute, 120°F is the minimum temperature predicted to prevent condensation.

The reason for operating the wind tunnels with air-carbon dioxide mixtures is to investigate the aerodynamic effect of changing the working fluid properties. As shown by Figs. 7 and 8, this change also affects the aerodynamic performance of the wind tunnels. The data presented on each of these figures represent tunnel operation at a fixed physical geometry. The pitot and supply section pressures were measured with gas-composition-insensitive pressure transducers. The values of Reynolds number, Mach number, and local-to-critical-area ratio (A/A^*) were taken from Refs. 5 and 6 by multiple interpolation. Figures 7 and 8 show that, while the presence of carbon dioxide has a significant effect on Mach number, the tunnels operate at essentially constant aerodynamic local-to-critical-area ratio as might be expected. The small variation of this aerodynamic area ratio is attributed to the effect of the changing Reynolds number affecting the tunnel wall boundary layer thicknesses, and possible carbon dioxide condensation within the relatively cool tunnel wall boundary layers.

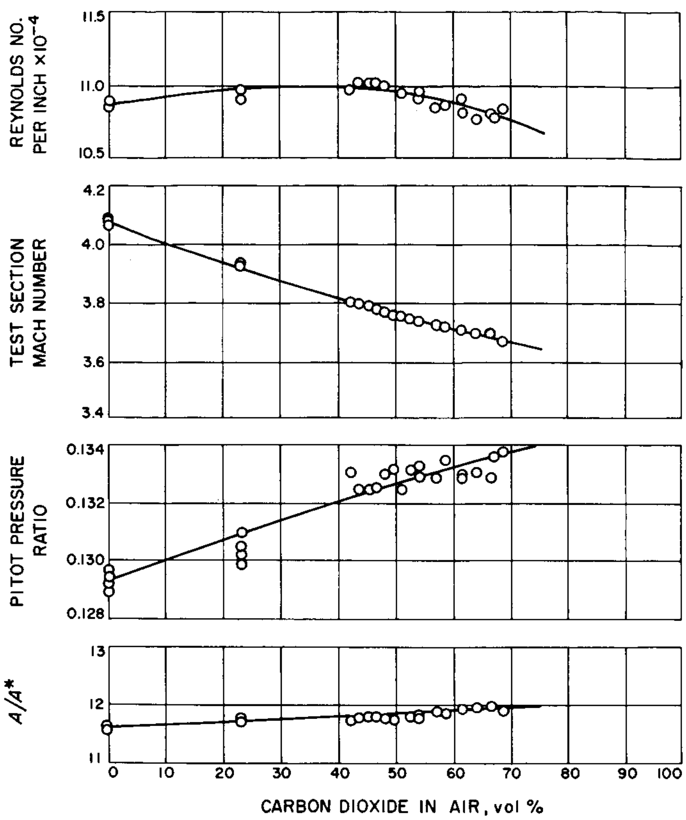

Fig. 7. Wind tunnel performance using CO_2 with supply section conditions of 1000 cm of Hg, 1300°F, and constant nozzle geometry

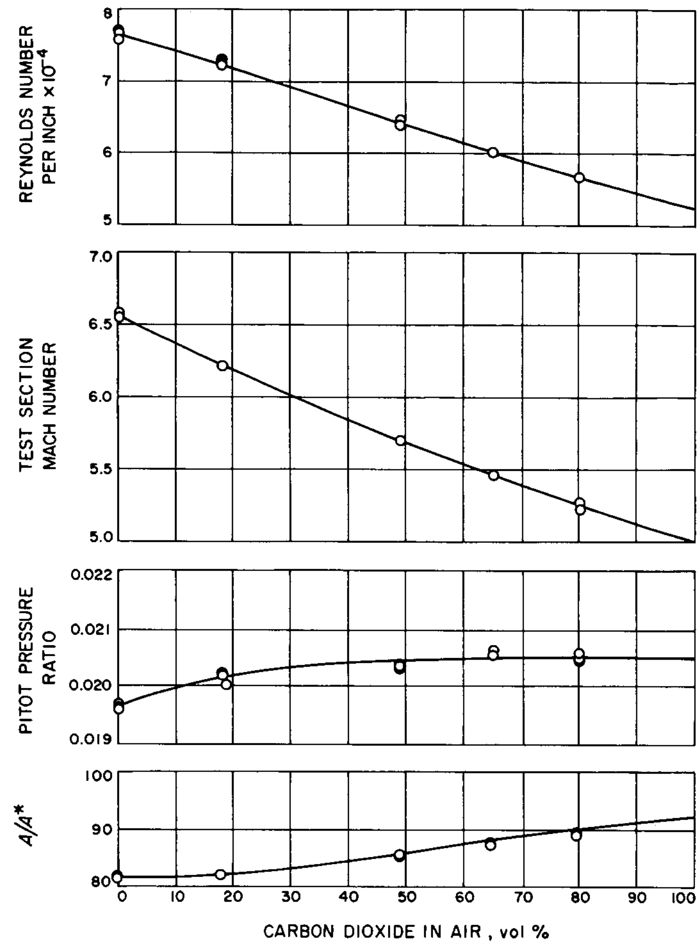

Fig. 8. Wind tunnel performance using CO_2 with supply conditions of 250 cm of Hg, 800°F, and constant nozzle geometry

In order to experimentally verify the tunnel aerodynamic conditions in the presence of carbon dioxide, pressures were measured on the surface of a sharp leading edged wedge. Figure 9 presents a sample of the resulting data. In this figure, the aerodynamically effective wedge angle has been computed from tunnel supply section, pitot, and wedge surface static pressures by use of the tables of Refs. 5 and 6. As shown by Fig. 9 this aerodynamically effective wedge angle exceeds the geometric angle by about one-half of a degree. This angular difference is attributed to boundary layer growth. The small angular slope vs Reynolds number indicated by these data is attributed to the customary boundary layer growth pattern, possible leading edge effects and, for the 20-deg wedge angle, possibly base pressure suction within the subsonic boundary sublayer. Similar slopes are apparent in data taken at other Reynolds number ranges.

Figure 9 also presents values of the partial derivative of Mach number vs wedge angle, at conditions of constant wedge-static-to-free-stream-pitot pressure ratio, as computed from the aerodynamic function tables. By use of this partial derivative, the apparent angle data scatter of about $\pm$ 0.1 deg may be interpreted as a free-stream-Mach-number uncertainty of less than $\pm$ 0.1. It is significant to note, however, that there is no apparent trend as a function of the percent of carbon dioxide present.

Figures 10 and 11 present the measured drag of a sting-supported sphere (sting-to-sphere-diameter ratio of 0.3) on very expanded scales to enhance inspection for small trends. From the conventional sphere drag coefficient (based on dynamic pressure), it would appear that there is a small effect from carbon dioxide. However, when the same data are presented as a modified drag coefficient, based on pitot pressure rather than dynamic pressure, no effect from carbon dioxide is apparent. The use of this modified drag coefficient has also successfully correlated results in Argon (Ref. 7) with those in air. The data in Fig. 11 fall within the $\pm 1\frac{1}{2}\%$ data band of Ref. 8. Reference 9 presents additional samples of aerodynamic data obtained in air-carbon dioxide mixtures at JPL.

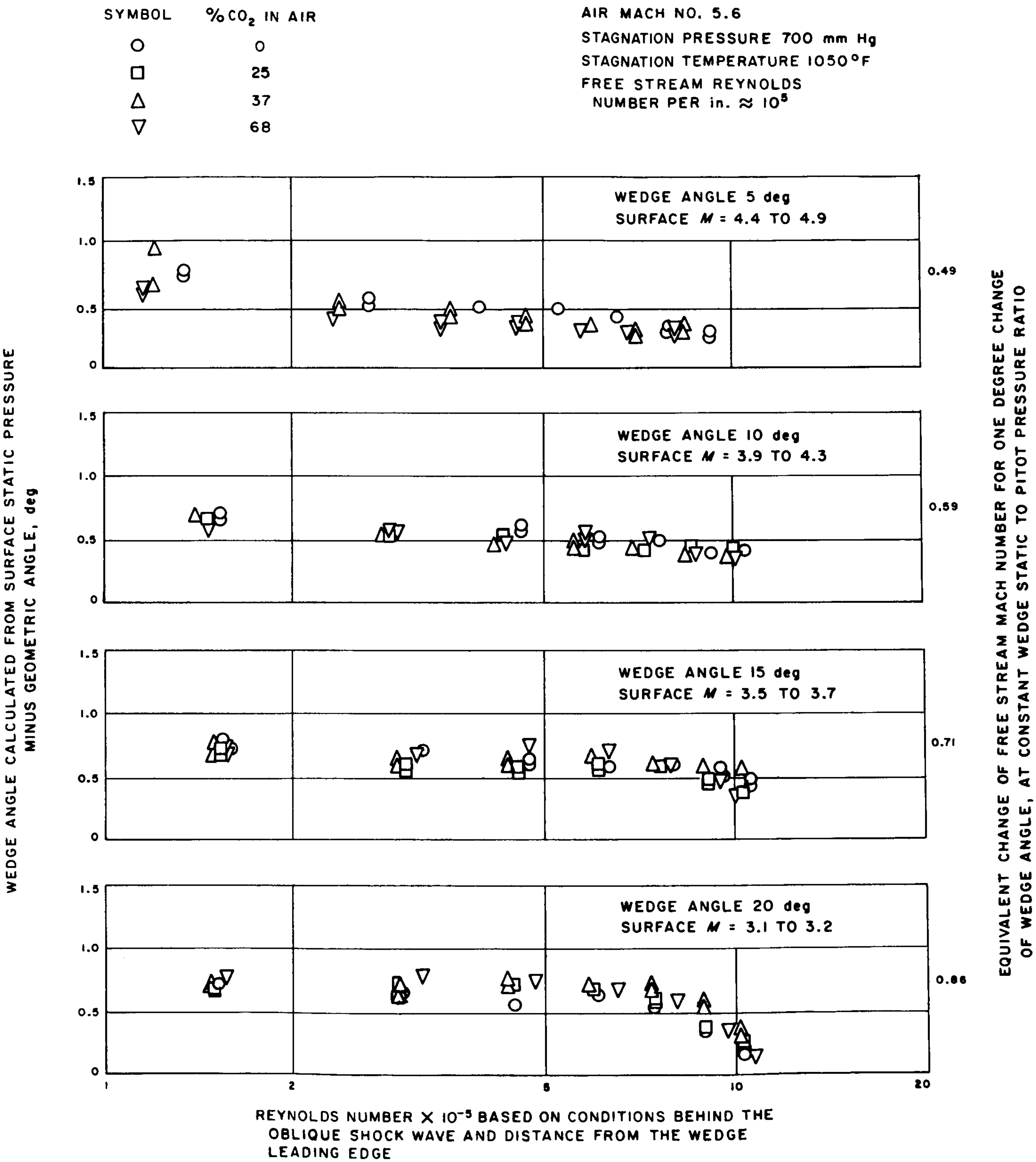

Fig. 9. CO_2-air flow over a wedge

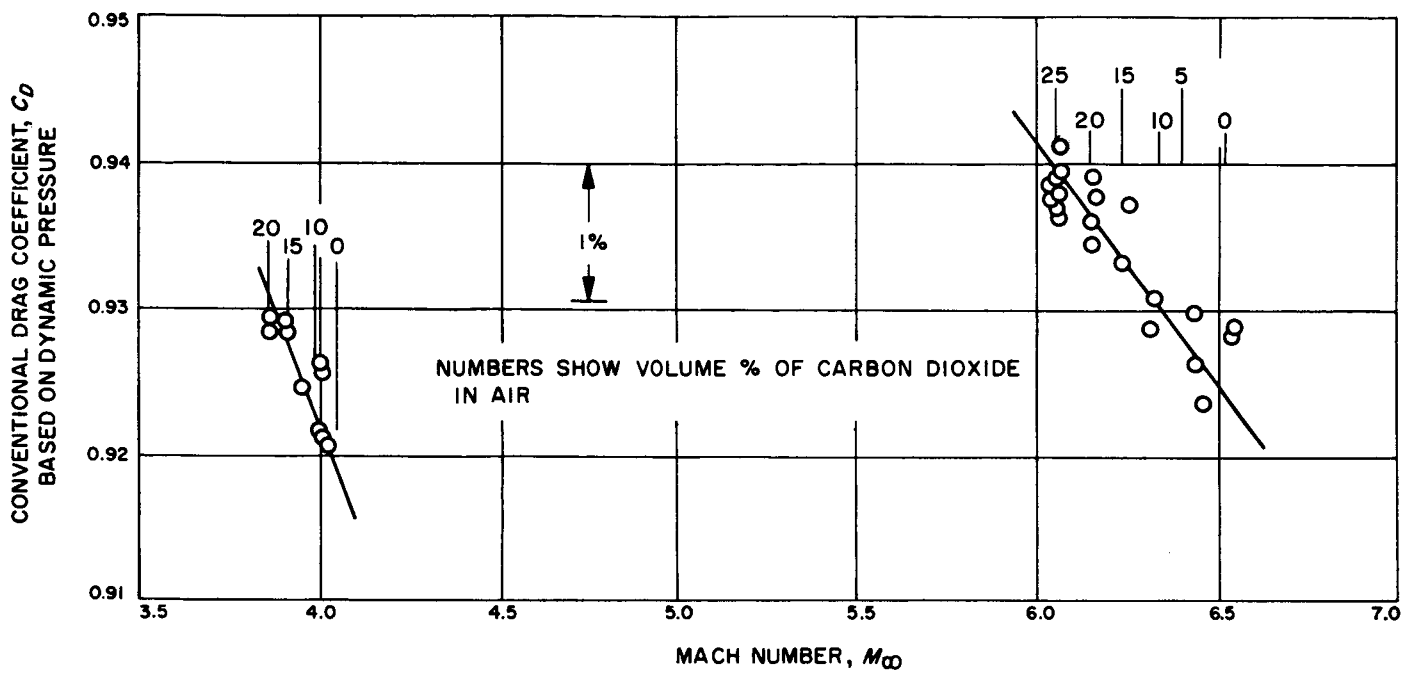

Fig. 10. Sphere drag in air-CO_2 mixtures, based on dynamic pressure

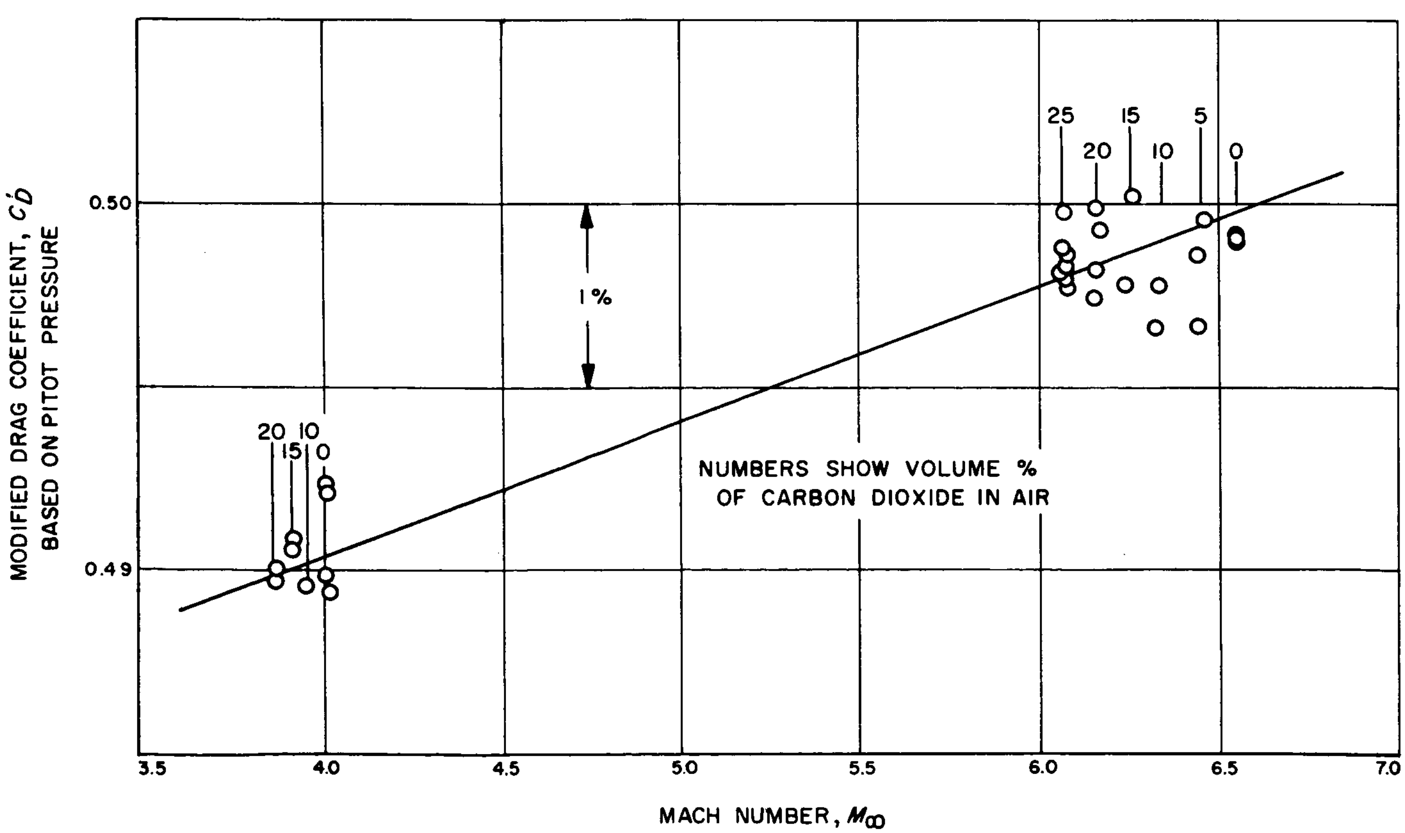

Fig. 11. Sphere drag in air-CO_2 mixtures, based on pitot pressure

IV. CONCLUSIONS

Operational techniques to utilize the JPL wind tunnels as multigas facilities, using air-carbon dioxide mixtures, have been presented. Samples of the resulting data presented indicate that these facilities perform quite close to analytical predictions, and this procedure may be considered as an established testing technique.

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